Microwave Photoresistance Measurements of Magneto-excitations near a 2D Fermi Surface

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Abstract

We report the detection of magneto-excitations, *i.e.* the cyclotron (CR) and magnetoplasmon (MPR) resonances, near the Fermi surface of a high-mobility two-dimensional electron system (2DES), by microwave photoresistance measurements. We observe large amplitude photoresistance oscillations originating from higher order CR, *i.e.* transitions between non-adjacent Landau levels. Such transitions are drastically enhanced in low magnetic field as compared to those previously known in the high field limit. The scattering time of the CR is found to be nearly one order of magnitude larger than that of the Shubnikov-de Haas oscillations. Finally, distinct photoresistance peaks are observed in addition to the CR features. They are identified as resonances of the low-frequency MP modes at a cut-off wavelength, determined by the width of the 2DES sample.

1

Low-energy collective excitations in a quantum Hall system both in the bulk and at the edges of the quantum fluid are of intense current interest[1]. In particular their electrodynamical response to a high frequency (ω), finite wavevector (q) probing field is believed to yield information complementary to dc transport measurements, for example on the internal structure of the edge states[2].

The relevant energy of these excitations is dictated by the Coulomb interaction, and is typically in the range[1] of 1 to $10K$. However, established experimental techniques have largely been limited to the high-energy regime where the cyclotron energy $\hbar\omega_c$ is comparable to the Fermi energy ε_F of the two-dimensional electron system (2DES). For example, dynamical transport measurements of the cyclotron (CR)[3,4] and magnetoplasmon resonances (MPR)[5−7] of a 2DES have been obtained by employing far-infrared (FIR) spectroscopy[8] down to about 10 $cm^{-1}(15K)$. Only recently have spectroscopic measurements in the low-energy regime, *i.e.*, millimeterwave frequencies, become available[9,10].

In this work we report the detection of CR and MPR near the Fermi surface ($\hbar\omega_c \ll \varepsilon_F \approx 80K$) of a high-mobility 2DES by microwave photoresistance[11] measurements. Unexpectedly, in a high-mobility GaAs-AlGaAs 2DES subject to a *weak* magnetic field, we observe giant photoresistance oscillations associated with higher order CR, *i.e.*, transitions between non-adjacent Landau levels (LL). Such transitions have previously been seen in CR experiments in the high magnetic field (B) regime[3] and have been explained via an analysis of short-range scattering potentials[12]. In the high B limit, however, the amplitude of even the second order CR is rather small. The dramatic enhancement of the higher order CR observed here is attributed to the mixing of many LLs in a weak B field[13]. We have also observed distinct photoresistance peaks associated with the dispersion of the MP modes. These peaks occur at a distinct cut-off wavelength of the MP mode, given naturally by the width of the sample.

Our samples are standard Hall bars lithographically defined (width $200\mu m$) and etched from modulation-doped MBE GaAs-AlGaAs heterostructures. While similar results have been obtained from a variety of samples, data from only one sample are presented here unless otherwise indicated. The sample has an electron density $n = 2.0 \times 10^{11} cm^{-2}$, and a

mobility $\mu \approx 3.0 \times 10^6 cm^2/Vs$, obtained by a brief illumination from a red light-emitting diode. The distance between the electrons and the Si doping layer is $d_s \approx 700\mathring{A}$. Coherent, linearly polarized, millimeter wave radiation from a solid state source of tunable frequency $f = \omega/2\pi$ from 30 to $150GHz$ (1.5 to $7.5K$) is guided via an over-sized waveguide to the sample. The sample is immersed in the ^3He coolant of a sorption-pumped ^3He refrigerator at a constant temperature (T) ranging from 0.4 to $1.8K$. The output power of the source is from 10 to $50mW$; between the source and the waveguide an attenuator is placed for varying the incident power to the sample. B is applied perpendicular to the sample surface. We measure the magnetoresistance employing a standard low frequency (3 to $7Hz$) lock-in technique.

In FIG.1 we show the normalized magnetoresistance $R_{xx}^\omega(B)/R_{xx}^\omega(0)$ under microwave illumination for several values of ω. The R_{xx}^ω is measured by sweeping B while ω and T are held constant. Without illumination (dotted line), the sample starts to exhibit normal Shubnikov-de Haas (SdH) oscillations at an on-set field $B_{SdH} \sim 2.0kG$. New, large amplitude resistance oscillations appear under illumination, arising from a correction to the magnetoresistance owing to the resonant absorption of microwave radiation[13]. The correction, or the photoresistance $\Delta R_{xx}^\omega(B) = R_{xx}^\omega(B) - R_{xx}^0(B)$ generally alternates in sign with increasing B so as to form an oscillatory structure which is roughly periodic in $1/B$ (see e.g., the trace at $45GHz$). With increasing ω, such structure shifts to higher B in an orderly fashion, but largely remains limited to a low B range where the SdH is absent.

The B positions of the $\Delta R_{xx}^\omega(B)$ peaks are seen to satisfy a resonance condition in which the microwave quantum equals an *integer multiple j* of the cyclotron energy $\hbar\omega_c = \hbar eB/m^*$, where m^* is the electron effective mass,

$$hf = j \cdot \hbar\omega_c, \text{ or } j = \omega/\omega_c. \tag{1}$$

Thus, for $j > 1$, the structure is due to microwave-induced transitions between non-adjacent LLs, or higher-order CR. More surprisingly yet, a distinct ΔR_{xx}^ω peak emerges for frequencies between roughly $60GHz$ and $100GHz$, with an amplitude and a width in B comparable to

3

those of the CR features. The B field position of this additional peak shifts from the $j = 2$ towards the $j = 1$ CR peak as ω increases, with the feature eventually merging with the $j = 1$ peak. This is the MP resonance to which we will return.

While higher-order CR has previously been observed, the low B field regime of this work produces a strong mixing of multiple LLs. This results in a dramatic enhancement of the amplitudes for higher-order transitions, as discussed in Ref.13. In fact, under our low B condition the photoresistance is caused by the lowest-order corrections to the conductivity in a microwave field, which is given by[13]:

$$\Delta\sigma_{xx}(\omega) \propto \cos(2\pi\omega/\omega_c) \cdot \exp(-2\pi/\omega_c\tau). \qquad (2)$$

Several comments are appropriate here. While such photoresistance oscillations may resemble those of SdH, they differ in the following crucial aspects. First, the period is controlled by the ratio ω/ω_c rather than $\varepsilon_F/\hbar\omega_c$, indicating a purely classical effect. The absence of the Fermi energy ε_F in Eqn.2 also implies that the effect does not depend on the electron density. This is supported by similar data obtained from other samples of differing density. In addition the oscillation is expected to have very weak T dependence within a certain temperature range. Indeed the amplitude of the oscillation does not change significantly from 0.4 to $1.8K$, whereas the SdH exhibits very strong T dependence. Finally, the damping exponential contains a factor of 2 as compared to the usual Dingle factor in the SdH formalism[14].

Having identified the higher-order CR from the photoresistance, we have further determined respectively the mass m^* and the scattering time τ_{CR}. From Eqn.1, $j = \omega/\omega_c = \omega m^*/eB$, therefore for a fixed ω we may plot the multiplicity index j against the inverse magnetic field $1/B$, to obtain the value of m^*. Such a plot is shown in FIG.2 for the data at $120GHz$ where the oscillations are seen to persist to as high as $j = 7$. We include here both the integer $j = 2, 3, ...$ (maxima in photoresistance) and the half integer $j = 3/2, 5/2, 7/2, ...$ (minima), since both are described by Eqn.2. The effective electron mass yielded is $m^* \approx 0.066$ (in units of the free electron mass), close to the known value

0.068 of the band electron mass in GaAs.

In order to estimate τ_{CR}, we compare the model of Ref.13 to the data, as shown in FIG.3. This model takes into account the scattering corrections for each harmonic, and therefore is improved in details over Eqn.2. The dotted line represents the calculated conductivity $\sigma_{xx}^{\omega}/\sigma_{0}^{\omega}$ (and hence the absorption) with a scattering parameter $\omega\tau_{CR}$. As shown here, the data of the photoresistance (solid line) and the $\omega\tau_{CR} = 10$ curve agree with each other not only in periodicity but in the relative amplitude of the harmonics as well, yielding[14] a scattering time $\tau_{CR} \approx 16ps$. This value compares well with that obtained from the simpler Eqn.2 (shown in the inset to FIG.3).

The SdH scattering time $\tau_{SdH} \sim 1ps$ in the same sample determined by a Dingle plot (not shown) is, however, much smaller than τ_{CR}. We also estimate the transport scattering time from the dc mobility $\mu = e\tau_t/m^*$ to be at $\tau_t \approx 100ps$. Comparing scattering times in these three regimes we speculate that the CR oscillations observed here may not be sensitive to certain properties such as the density inhomogeneity in a 2DES. It is well known[15] that the density inhomogeneity contributes to an underestimate of the experimental value of τ_{SdH}. On the other hand, there is no existing theory which deals with photoconductivity in realistic samples. We note also that a very large CR scattering time, even larger than that of the transport scattering time, has been observed in the extreme magnetic quantum limit in a GaAs-AlGaAs system[4].

We have further confirmed our CR results over a wide range of ω. In accordance with Eqn.1, the energy required for higher-order CR, for a set of *integer* j, is expected to form a fan diagram against the B field position of each resistance maximum. In FIG.4, we plot our data in just such a diagram covering our ω range. The open symbols represent the data for each branch $j = 1, 2, 3$, and the dotted lines represent the fans calculated using a value of 0.068 as the electron mass. The higher-order extrema ($j = 2, 5/2, 3, ...$) data are described well by Eqn.1, over a wide range of frequencies. However, the fundamental CR, i.e., the $j = 1$ transition energy, is roughly lower by 10% as compared to the calculated cyclotron gap. The origin of the discrepancy between the calculated value and the data at $j = 1$ is

unclear at this point, especially in light of the good agreement obtained for the higher-order branches.

We devote the rest of the paper to a discussion of the magnetoplasmon. The MPR data, both for the same sample ($n = 2.0 \times 10^{11} cm^{-2}$, filled circles) and for an additional sample having a lower density ($n = 1.7 \times 10^{11} cm^{-2}$, filled squares), are shown in FIG.4. The existence of these peaks in our low magnetic field measurements is rather puzzling at first glance. On the one hand, the magnetic field dependence of the resonance energy resembles, when plotted in this fashion, the finite-wavevector MP that has been seen[7] in a grating-modulated 2DES at high B fields. On the other hand it is necessary to introduce a finite q in the 2DES for the MP resonance to take place.

In the simplest approximation, which ignores non-local interactions, the dispersion of a long wavelength ($\omega/c < q \ll q_F$, where q_F is the Fermi wavevector) plasmon is known to be[5–7]:

$$\omega_P^2(q) = \frac{ne^2q}{2\epsilon\epsilon_0 m^*} \tag{3}$$

where ϵ is the effective dielectric function of the surrounding media. In the presence of a perpendicular magnetic field, the plasmon has a low cut-off frequency given by the cyclotron frequency $\omega_c = eB/m^*$ and the coupled cyclotron-plasmon modes or the MP dispersion then becomes

$$\omega_{MP} = \sqrt{\omega_c^2 + \omega_P^2} \ . \tag{4}$$

The MP dispersion dictates that the MP resonances can be observed only by coupling to a finite momentum transfer q, usually via a spatially modulated radiation field or electron density[5–7]. The observation of MP absorption at a specific ω in an un-patterned 2DES implies, then, that a finite q must be selected in the process. It turns out that what we have observed are just the resonances of the low-frequency MP modes at a cut-off wavelength given by the width of the 2DES sample.

Empirically we fit the MP dispersion (Eqns.3,4) to our data to find the value of q, using a mass $m^* \approx 0.068$ and a dielectric constant $\epsilon = 12.8$. Simple fits result in, respectively, $2\pi/q \approx$

6

$204\mu m$ (for the $n = 2.0 \times 10^{11} cm^{-2}$ sample) and $229\mu m$ ($1.7 \times 10^{11} cm^{-2}$). These values compare quite well with the lithographic width ($\sim 200\mu m$) of both Hall bars, considering that several factors contribute corrections to the idealized 2D plasmon dispersion given by Eqn.3. In the long-wavelength limit, the finite thickness of the 2D electron layer and the uncertainties of the dielectric function ϵ are thought to be the main corrections[7]. The former in particular will soften the plasmon frequency, therefore rendering an overestimation of the width. Depletion of the electrons near the edge will, of course, reduce the effective width, but such an effect is expected to be negligibly small here.

It is then convincing that a low-frequency branch of MP is excited by microwave fields in our samples, and detected by our photoresistance measurements. We further note that since polarization of the microwave E field is perpendicular to the length of the Hall bar (inset FIG.1), the MP observed are transverse to the current. The MP modes observed here can then be viewed as the standing waves in a 2D waveguide defined by the Hall bar, and these are just the low-frequency cut-off modes. In fact, we have also observed higher-order MP modes associated with integer fractions of the sample width.

To summarize, we have identified the oscillatory photoresistance as the CR of electrons in a weak magnetic field. We emphasize that the exceptionally strong higher-order harmonic absorption observed here is due to the presence of short-range scatterers, ubiquitous in even very clean GaAs-AlGaAs heterostructures, and that the presence of higher LLs favors large amplitudes for the higher-harmonic absorptions. The scattering time in this regime appears, however, an order of magnitude larger than that determined by the Dingle plot in the SdH regime. This observation may be attributed to the different role played by inhomogeneity in these two regimes. We have also identified distinct resonances of the low-frequency magnetoplasmon modes at a cut-off wavelength, determined by the width of the sample. This work thus establishes a method for the detection of low-energy magneto-excitations close to the Fermi surface of a 2DES. It is our hope that this experimental technique of microwave resonant photoconductive spectroscopy can be readily extended to a number of low-dimensional electron systems.

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FIGURES

FIG. 1. Magnetoresistance in a weak magnetic field under millimeter wave illumination at several fixed frequencies $f = \omega/2\pi$, measured at a constant temperature of $T = 1.7K$. The data exhibits large amplitude photoresistance oscillations for all frequencies. A distinct, additional peak (arrow) emerges at high frequencies. The inset depicts the microwave E field polarization with respect to the sample.

FIG. 2. Photoresistance at $f = 120GHz$ showing multiple extrema persisting to $j = 7$. The inset is a plot of the order index j against the inverse magnetic field position of resistance extrema, yielding an electron mass of $m^* = 0.066m_0$.

FIG. 3. Comparison of photoresistance oscillations from experiment (solid line) with the dissipative conductivity from the theory of Ref.13(dotted line). The theoretical curve assumes $\omega\tau_{CR} = 10$, corresponding to a scattering time of 16 ps. Inset: plot of the oscillation amplitude vs. the inverse of the magnetic field, consistent with a scattering time $\tau_{CR} \approx 16$ ps obtained from Eqn.2.

FIG. 4. Resonant energy $\Delta = \hbar\omega$ (in Kelvin) versus magnetic field B for resistance extrema $j = 1, 2, 3$ (open circle) and $j = 5/2, 7/2$ (open square). The dotted lines represent the value of $0.068m_0$ known for the band electron mass in GaAs. The filled circle (filled square) is the data of the magnetoplasmon resonance in the sample having an electron density $n = 2.0 \times 10^{11}cm^{-2}$ $(1.7 \times 10^{11}cm^{-2})$ and a Hall bar width $W = 195\mu m$ $(200\mu m)$. The solid lines are the fits of the magnetoplasmon dispersion to each sample, as discussed in the text.
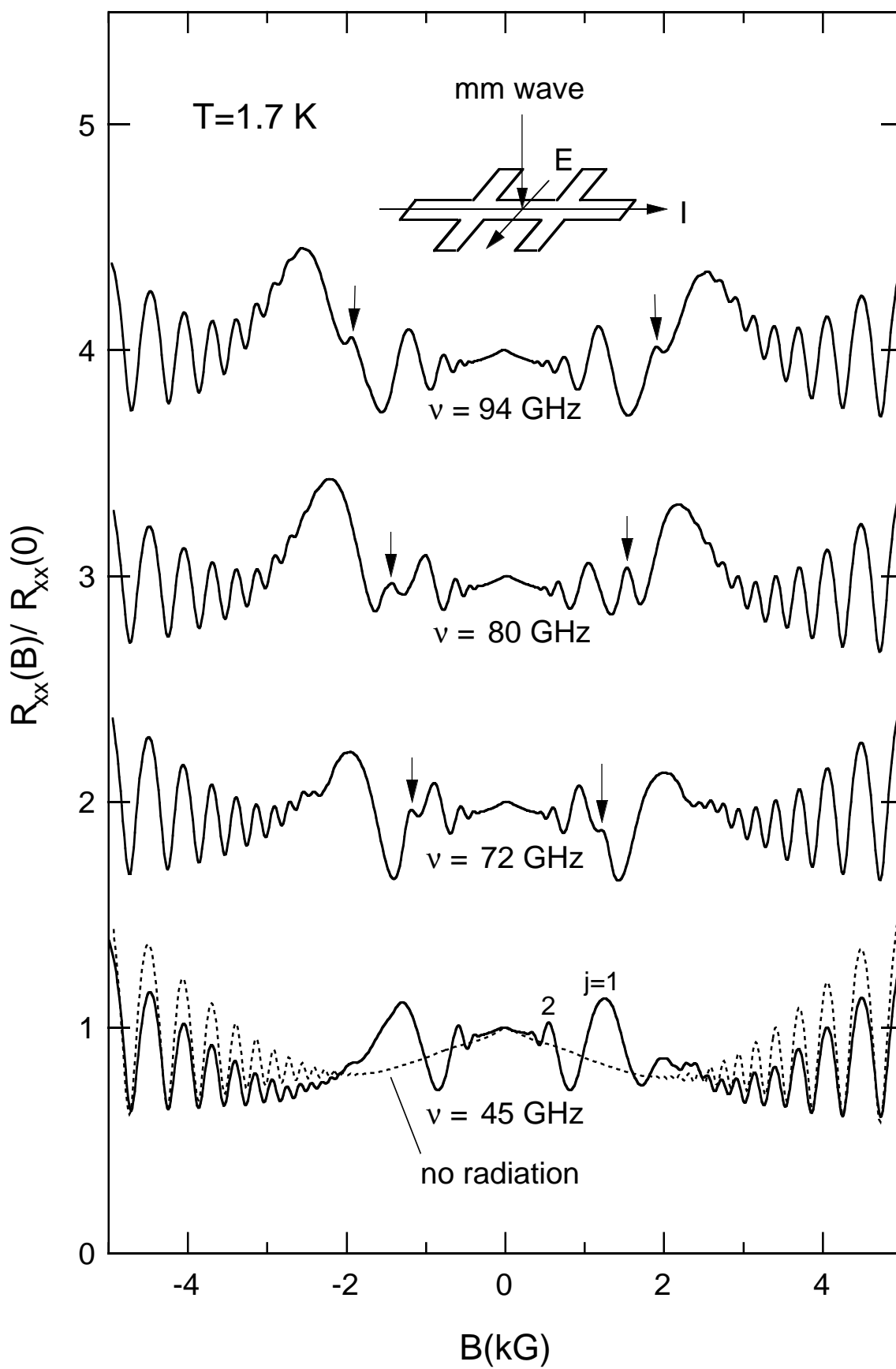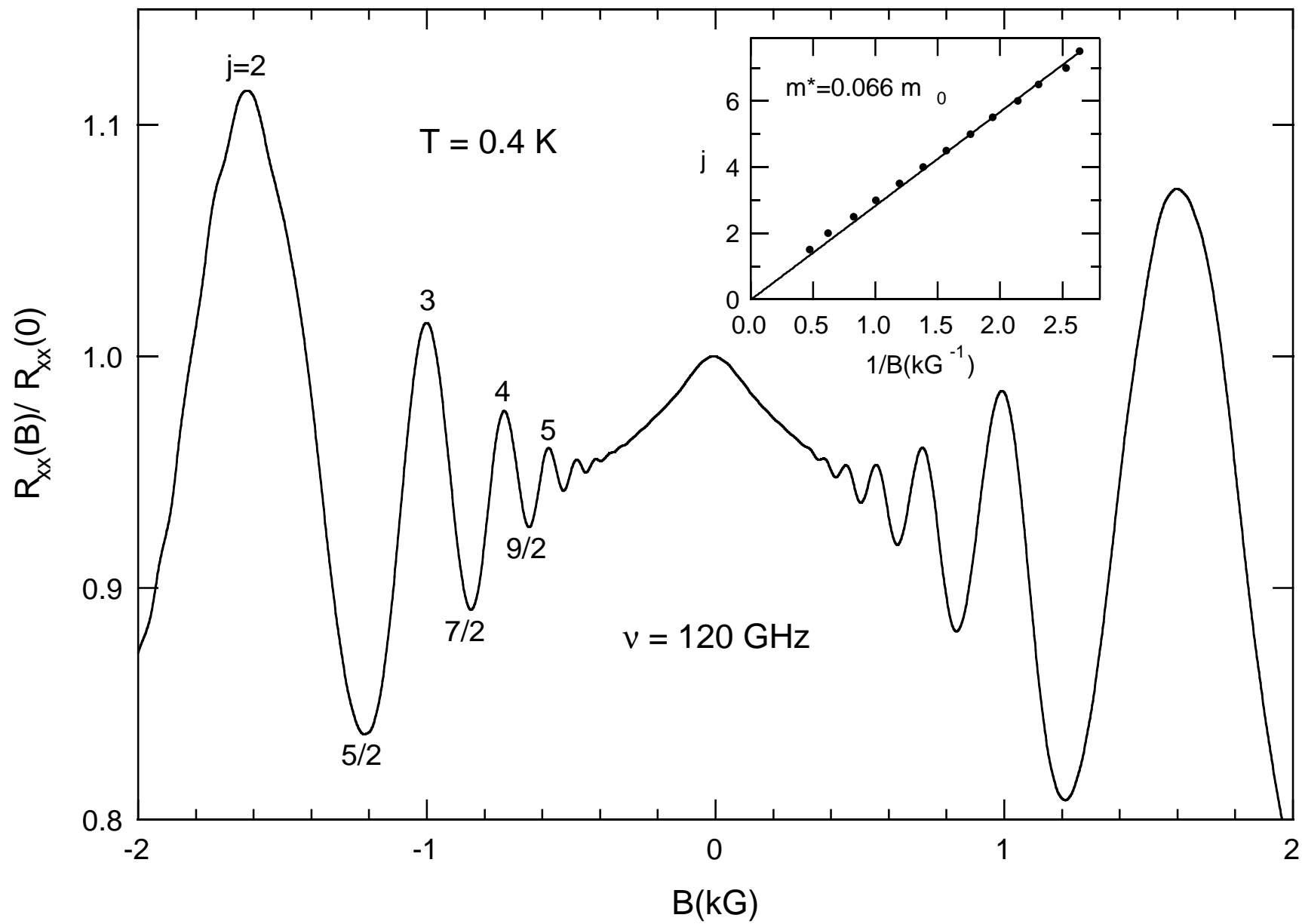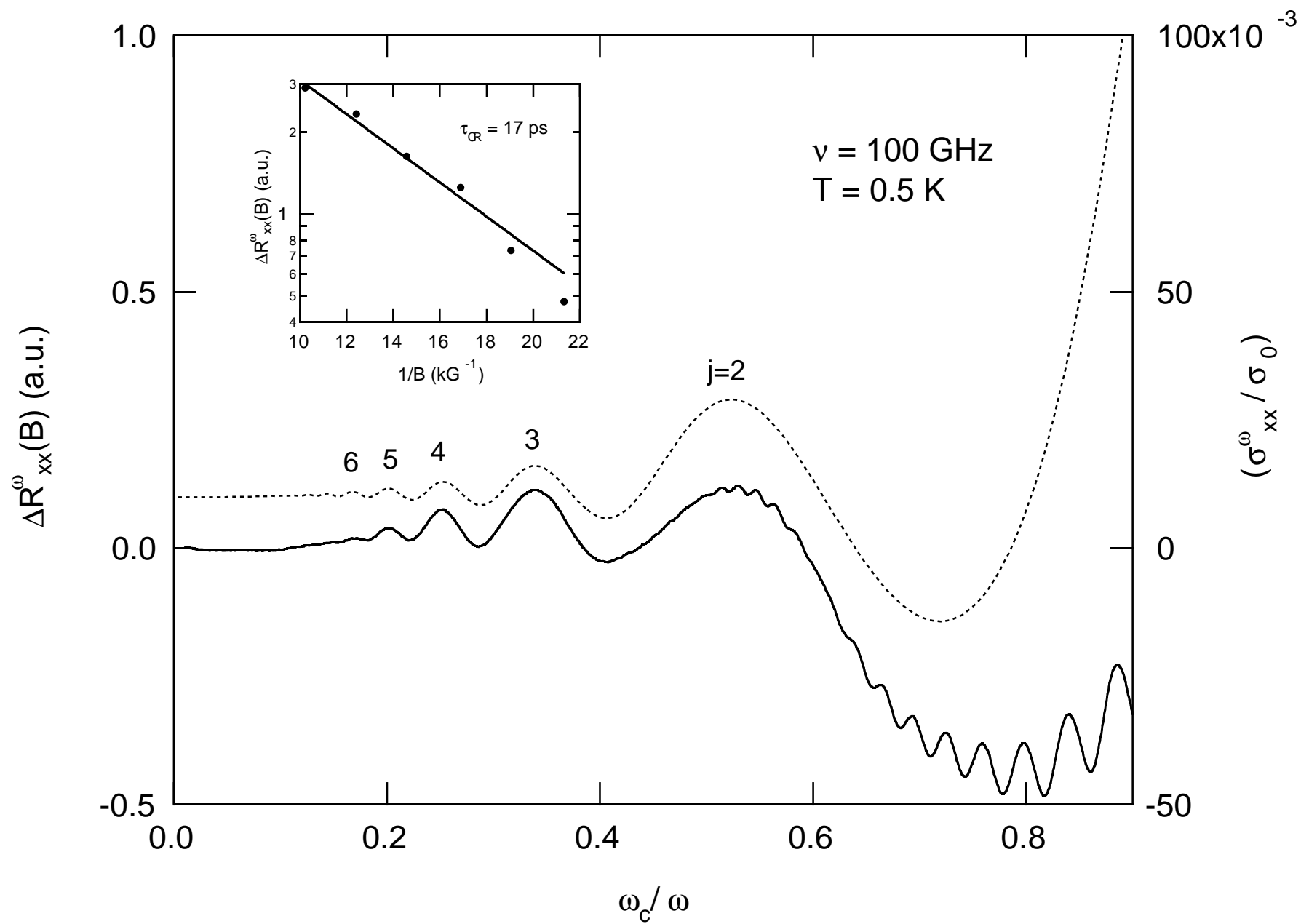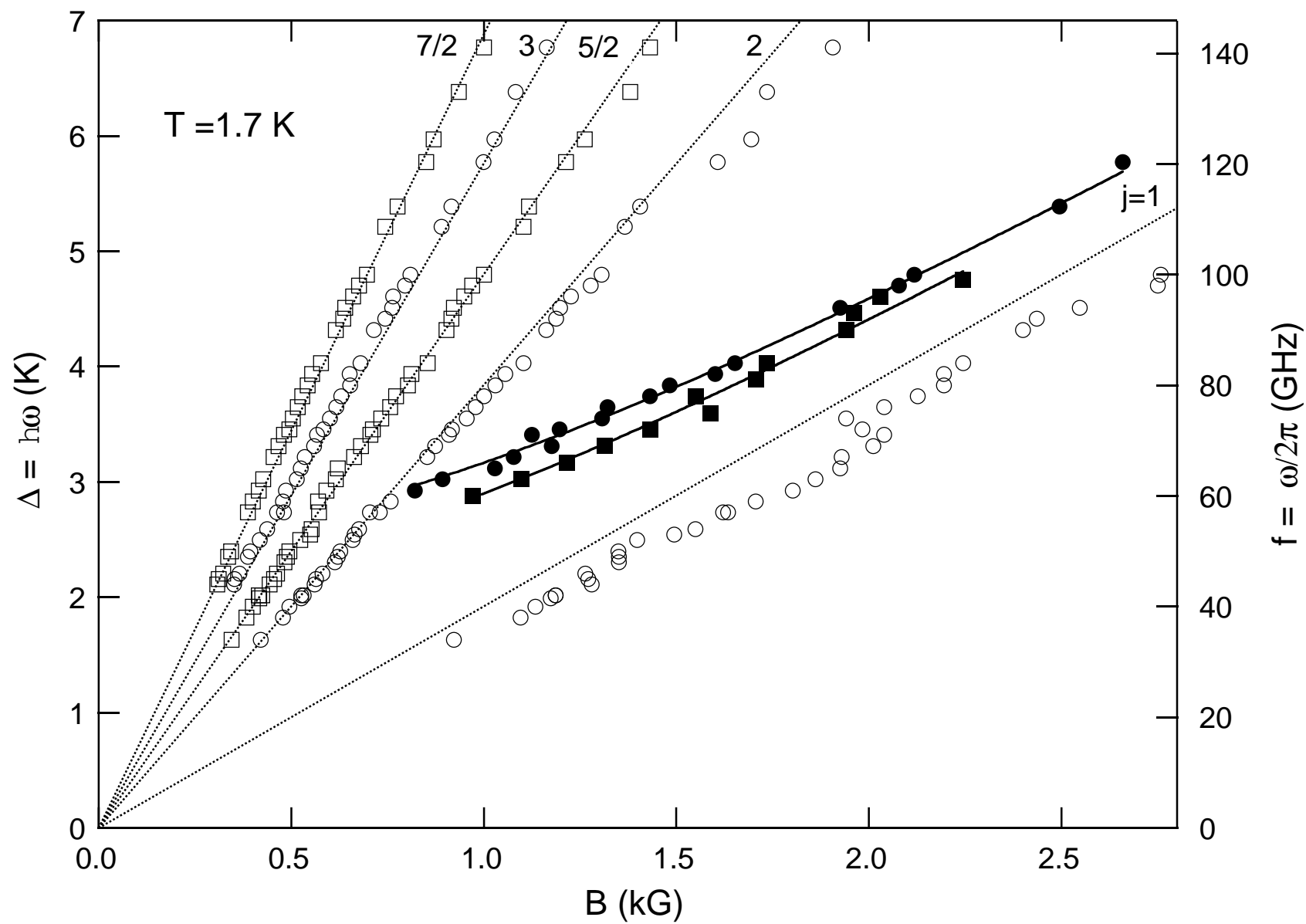
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